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VIBRATION CONTROL OF STRUCTURES USING MAGNETO-RHEOLOGICAL DAMPERS WITH H_∞ METHOD

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In this study, the vibration mitigation of the structures under the earthquake excitation using magneto-rheological (MR) damper is researched. For this purpose, one MR damper is installed to an eight story structure and the system performance is investigated. MR damper is installed between the second floor and the ground. The MR damper is a semi-active control device that can be controlled by only the voltage transmitted to the electromagnetic coils. Since the MR damper is a semi active device, damping force can be changed by applied voltage. Therefore, determination of the applied voltage is important for vibration reduction. A robust controller is designed for determination of the MR damper voltage. H_∞ method and model reduction approach are used for robust control design and application. The performance of the proposed method is tested by numerical simulation on the semi active structural system with MR damper. The performance of the control algorithm and the effect of the MR damper arrangement is evaluated using earthquake (El-centro earthquake) data. The results are compared with situations in which MR damper is not connected and when the MR damper is situation of semi-active controlled. The evaluations are based on the displacement and acceleration responses. The simulation results showed that the arrangement of the MR damper connected between the second floor and the ground is effective in reducing the vibration amplitudes.

Keywords: Structural control, MR damper layout, H_∞ robust control, Simulation study.

1 INTRODUCTION

The control of linear and nonlinear systems equipped with semi-active devices is an interesting subject that can be studied both experimentally and theoretically (Atabay and Ozkol (2013); Castao *et al.* (2011); Cetin *et al.* (2011); Cornejo and Alvarez-Icaza (2011); Paksoy *et al.* (2014); Cetin *et al.* (2011)). Active and semi-active systems can be controlled electronically. Passive systems are simple and classical systems that are currently used. Semi-active systems can act as both active and passive systems. Their performance is similar to active systems. Because they can act as a passive system in the case problems of control systems and they are more reliable than active systems.

A number of studies are conducted regarding the control of the MR damper and the arrangement of multiple MR dampers. Dyke *et al.* (1998) employed MR dampers on the first floor of a three-story structure. Dyke *et al.* (1996) applied a clipped optimal control algorithm, which was previously tested via simulations (Dyke *et al.* 1998), by connecting the MR damper to the test model between the ground floor and first floor.

Jansen and Dyke (2000) implemented MR dampers in a building model with six DOF; the MR damper was laid out on the first two floors in a parallel configuration. Aldemir (2009) developed a causal sub-optimal control, placing an MR damper on the first floor of the base-isolated structure with 2 DOF. The results were compared with instantaneous optimally controlled and uncontrolled situations, and the presented control algorithm was shown to be effective in reducing the effects of earthquakes on the structure. Bitaraf *et al.* (2010) used two MR dampers, which were placed on the first and second floors of the structure, and applied two control methods which are direct adaptive control based on a simple adaptation technique and a genetic-based fuzzy control. Cetin *et al.* (2011) used a six-story steel structural model, and an MR damper was implemented on the first floor. A nonlinear adaptive controller based on the Lyapunov technique, which can balance parametric uncertainties, was used to command the MR damper voltage. This study reports the control and arrangement of one magneto-rheological (MR) damper that is used to reduce structural vibrations. H_∞ method and model reduction approach are used for robust control design and application. The simulation results showed that the arrangement of the MR damper connected between the second floor and the ground is effective in reducing the vibration amplitudes.

2 PROBLEM FORMULATION

In this study, MR damper layout in an eight-story steel structure is investigated, as shown in Figure 1. The mathematical movement of the building model is shown in Figure 1 and can be given as

$$M_s\ddot{x}(t)+C_s\dot{x}(t)+K_s x(t)=-Hf(t)-M_s L\ddot{x}_g(t) \tag{1}$$

where *f(t)* is the damping force of the MR damper and M_s, C_s, and $K_s \in \Re^{8x8}$ are the mass, damping and stiffness matrices, respectively. $\ddot{x}(t),\ \dot{x}(t)\ and\ x(t) \in \Re^{8x1}$ are the acceleration, velocity and displacement vectors, respectively.

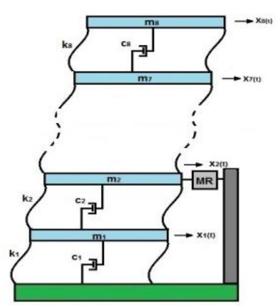

Figure 1. The MR damper is located between the second floor and the ground.

Unidirectional horizontal movement is considered in this model. The relative displacement vector for the model is $x=\begin{bmatrix}x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8\end{bmatrix}^T$.The H vector indicates the placement of the control units. The MR damper is placed between the second floor and the ground, so $H_{MR2} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$. The seismic input vector is $L = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}^T$. $\ddot{x}_g(t)$ is the earthquake ground acceleration.

3 ROBUST CONTROLLER DESIGN

Considering the structural system modeled in the previous section, the full-order model of the system in physical coordinates can be written in the state space model as follows:

$$\dot{x}_f = A_f x_f + B_f u, \;\; y_r = C_f x_f \tag{2}$$

where A_f, B_f, C_f and D_f, are the linear system matrices and given respectively, by

$$A_f = \begin{bmatrix} 0 & I \\ -M_f^{-1} K_f & -M_f^{-1} C_f \end{bmatrix}, \;\; B_f = \begin{bmatrix} 0 \\ M_f^{-1} F_f \end{bmatrix}, \;\; C_f = [C_y \quad 0], P_f(s) = \begin{bmatrix} A_f & B_f \\ C_f & 0 \end{bmatrix} \tag{3}$$

For the model order reduction, the system must be transformed from the physical space to the modal space. The equation in modal coordinates can be written for full order and reduced order models as

$$\ddot{\eta} + C_f \dot{\eta} + K_f \eta = H_f f \;, \;\; \ddot{\eta}_r + C_r \dot{\eta}_r + K_r \eta_r = H_r f \;. \tag{4}$$

When structural control is considered, controlling the first two modes provide good results for the earthquake hazard mitigation of structural systems and reduce the amplitudes. Differences between real systems and dynamic models are modeled as $\Delta_t(s) = P_f(s) - P_r(s)$. The two primary transfer functions in this control system are *S(s)* is defined as the sensitivity transfer function, and *T(s)* is the complementary sensitivity transfer function. When *T(s)* and Δ_t(s) are considered stable, using a W_T filter and provided that the upper limit of Δ_t(s) satisfies

$$\left|\Delta_t(j\omega)\right| \le \left|W_T(j\omega)\right| \tag{5}$$

a norm W_T condition from ω to z_2, the feedback system can be stable

$$\left\|W_T T(s)\right\|_\infty < 1 \tag{6}$$

The second aim of the H_∞ controller is to improve the performance of the feedback control system. The H_∞ norm condition can be written as

$$\left\|S(s)\right\|_\infty = \sup \bar{\sigma}[S(s)], \text{ (} \bar{\sigma} \text{ is maximum singular value of } S(s).) \tag{7}$$

where W_S is the filter for the system output. Thus, specifying the W_T(s) and W_S(s) filters in the control system satisfies both robust stability and response performance. This type of H_∞ controller is called a mixed sensitivity problem and is defined as

$$\left\| \begin{bmatrix} W_S S \\ W_T T \end{bmatrix} \right\|_\infty < \gamma \tag{8}$$

where γ is a design parameter that is positive. An important step in H$_\infty$ control is to determine the frequency shape filters. Additive uncertainty is used to select W_T. A filter should cover the uncertainty to provide robust stability. In this manner, frequency shape filters take the following form:

$$W_T = k_w \left(\frac{s^2 + 2\xi_{nm}\omega_{nm}s + \omega_{nm}{}^2}{s^2 + 2\xi_{dm}\omega_{dm}s + \omega_{dm}{}^2} \right) \quad (9)$$

where ω_{nm} is the frequency of the last controlled mode and ω_{dm} is the frequency of the first uncontrolled mode. The open- and closed-loop responses of the full order model is shown in Figure 2.

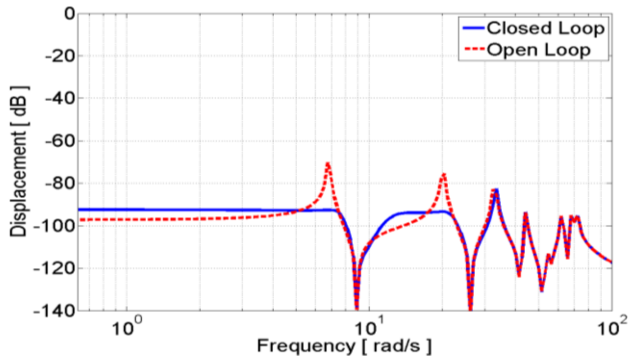

Figure 2. Open- and closed-loop responses of system.

3.1 Controller Application in Semi-Active System

The voltage of the MR damper is selected as follows (El-Kafafy and El-Demerdash, 2012; Lam and Lio, 2002):

$$\begin{aligned} &\text{If} \quad G(f_c - f_d)\text{sgn}(f_d) > V_{\max},\ v = V_{\max} \\ &\text{or}\ G(f_c - f_d)\text{sgn}(f_d) < V_{\min},\ v = V_{\min} \\ &\text{otherwise,} \quad v = G(f_c - f_d)\text{sgn}(f_d) \end{aligned} \quad (10)$$

where $V_{\max}$ is the maximum voltage in the MR damper, $V_{\min}$ is the minimum voltage in the MR damper, f_c is the force necessary for the system and is determined by the controller, and f_d is the force formed by the MR damper and is measured by the system. Finally, G is the MR damper control gain.

3.2 Simulation Results

The mass value of system for each floor is 107.5, and the mass matrix is $M_f = diag[107.5]_{8x8}$. Considering the connection with 8 bars made of spring steel, the stiffness of the system for each floor is evaluated as $k_{1-8} = 8*12EI/l^3 = 145152 N/m$

(Cetin *et al.*, 2011). According to the Rayleigh damping principle, if $\alpha_0 = 0.0265$ and $\beta_0 = 0.00011431$, $[C_s] = \alpha_0 [M_s] + \beta_0 [K_s]$, the damping coefficient is $C_{1,2,3,4,5,6,7,8} = 16.59 N.s/m$, and the controller gain G = 0.04. The maximum voltage $V_{\max}$ is 2 V, and the minimum voltage $V_{\min}$ is 0 V.

The time responses for the situation of the MR damper's layout (MR_2) is shown in Figure 3. The acceleration response is illustrated in Figure 4. The passive (MR damper disconnected) and H_∞ controlled situation is compared to determine the performance of the controller. The case in which the MR damper is only on the second (MR_2) is examined. The displacement responses of all floors are shown in Figure 3. Comparisons of uncontrolled and controlled cases for the MR damper's layout is depicted in Figure 3, respectively. The connection of the MR damper reduces the vibration of each floor. The amplitudes of the displacement in situation corresponding to the MR with the controller is lower than the displacement amplitude in the situation corresponding to the passive system (without the MR damper). The acceleration responses of each floor for the MR damper layout is shown in Figure 4. The connection of the MR damper and the application of the robust controller improve the acceleration responses of each floor.

4 CONCLUSIONS

In this study, an H_∞ robust controller is designed to command MR damper voltage, by placing an MR damper on second floor to reduce building vibrations during earthquakes. The designed controller is tested in an eight-story structural model. By simulation studies the performances of the controller and MR damper are investigated. Comparison is made among case when the MR damper is not connected and controlled with H_∞. The evaluations are based on the displacement and acceleration responses. The arrangement of the MR damper connected between the second floor and the ground is effective in reducing the vibration amplitudes. Furthermore, the designed controller clearly improves the system performance.

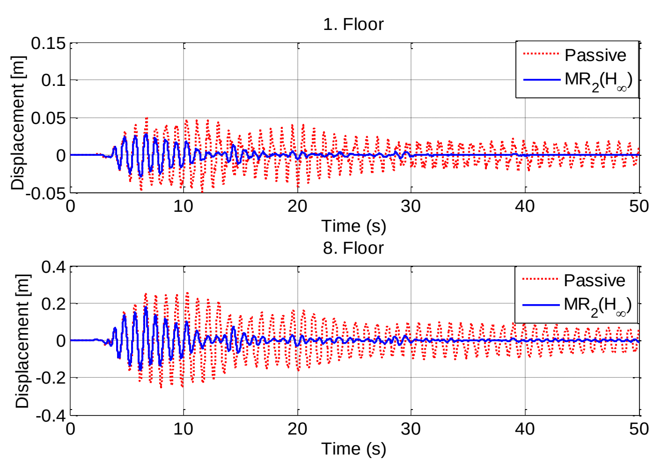

Figure 3. Displacements of (1-8) floors for the combinations of the MR damper layout: MR_2.

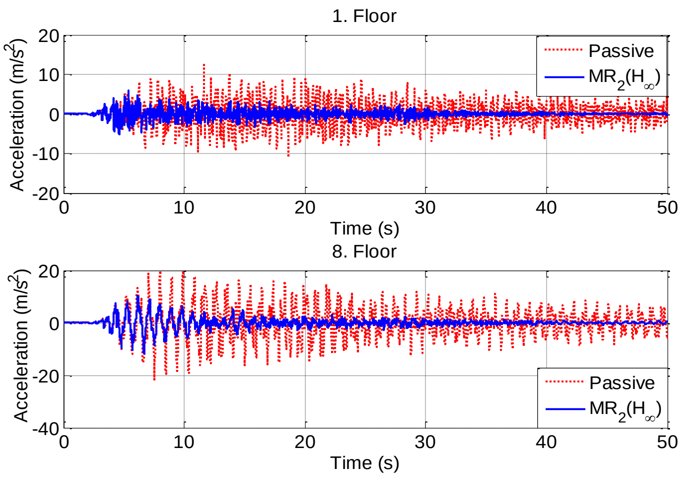

Figure 4. Accelerations of (1-8) floors for the combination of the MR damper layout: MR_2.

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